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Thermochimica Acta 451 (2006) 57–64
thermochimica acta
www.elsevier.com/locate/tca

Energy evaluation of the *Eucalyptus globulus* and the *Eucalyptus nitens* in the north of Spain (Cantabria)

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Received 2 December 2005; received in revised form 4 August 2006; accepted 11 August 2006
Available online 26 August 2006

Abstract

This work studied the potential use of the waste from *Eucalyptus globulus* and *Eucalyptus nitens* as energy crops, evaluating young and adult stages of both in all four seasons of the year with different moisture contents. The study was carried out made in Cantabria (North coast of Spain), located at latitude 43°28′N, and longitude 3°48′W. In this region, 29,513 ha are dedicated to the growth of *Eucalyptus*, with about 80% *E. globulus*, and 20% *E. nitens*. Six different plantations have been analyzed and their bioclimatic diagrams determined. After the collection of samples the potential energy of every sample was obtained, they were weighed, analyzed and burned, giving a *mean net calorific value* of 17,384 and 17,927 kJ/kg in the adult stage of *E. globulus* and *E. nitens*, respectively. The results for the young stage of both species were 17,708 and 18,670 kJ/kg. Moisture content in the samples has a great influence on power production. Finally, the economic and environmental consequences of these crop species for the region of Cantabria were analyzed.

Keywords: *Eucalyptus globulus*; *Eucalyptus nitens*; Energy crops; Forest waste; Net calorific value

1. Introduction

Spain, like many other countries in the European Union, does not have great reserves of petroleum or natural gas, which means there is a need for external energy, around 75% of the total demand [1].

This situation justifies the study and development of alternative power plants whose raw material is a local resource. In this way, the power dependency would be reduced and use of these energies will provide environmental benefit. One of the recommendations of the Kyoto Protocol, in its Article 3.3, is to increase the surface dedicated to forest, since this acts in two ways, they behave as carbon drains and they provide renewable raw material for a power plant [2].

The objective of this work is the evaluation of the power potential of the wastes of the two species of *Eucalyptus* grown in the region of Cantabria. These are evaluated in two stages of development, adult and young, for the four seasons of the year, and different moisture content. The determination of the calorific values was made for the different parts which the waste consists of. Moreover, the elementary chemical composition, the percentage of ashes after the combustion and an economic–environmental analysis were performed. The method followed for the power analysis determines the calorific power of these species by means of a static calorimetric pump [3].

This new approach contributes to the scientific literature with the thermal analysis of the young stage of the *Eucalyptus globulus*. The interest is based in the importance of this phase in the possible use of this species as an energy crop [4]. The results obtained from the adult stage corroborate the studies made in [5–7], where the wastes of this species in other geographic zones are evaluated. Regarding the *Eucalyptus nitens*, there is no available works on its energy evaluation. Thus, the study of this species was undertaken obtaining reference values which were compared with those obtained from the *E. globulus* analysis, both for adult phase and for the young.

The Cantabrian forests occupy more than 2/3 of the region's territory, and almost 60% of them are in use [8]. This represents a great forest surface that is still capable of significant growth. The average volume of wood generated annually in the area is

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0040-6031/$ – see front matter
doi:10.1016/j.tca.2006.08.009

Table 1
Forest surface in Cantabria [9]

Use	Hectares (ha)
Forest with trees	209,611
Forest without trees	145,201
Total forest	359,458
Total Cantabria	532,139
Eucalyptus	29,513

550,000 m^3, where 93% corresponds to *Eucalyptus*, 6% to *Pine radiate* and 1% to other native species [9,10], Table 1. These data reveal that the predominant productions are species of fast growth, as is the *Eucalyptus*.

The conventional use of the *Eucalyptus* is the paper industry, due to the high cellulose content of its wood. In this sector the useful part is taken, leaving in the plantation the rest of the tree (bark, branches, leaves, seeds, etc.), which could be used as fuel. Considering that the average density of the *Eucalyptus* is 740 kg/m^3 [11], this comes to be 378,500 t of useful wood. Usually the percentage of waste is 20% of the tree weight [12], which means that 95,000 t of wastes are abandoned annually in the plantations.

The predominant species in the coastal zones is the *E. globulus*, whereas in the mountains or in zones with a high probability of freezing, the suitable species is the *E. nitens*. The latter is highly resistant to cold temperatures, although the cellulose production is lower than that of *E. globulus*. Currently, the presence of insect plagues and fungi in the *E. globulus*, such as *Gonipterus scutellatus* [13,14], for the adult stage, and *Mycosphaerella molleriana*, in young [15], has caused this species to have lost importance in favour of the *E. nitens*, even in its natural area of development, which is the coastal zones.

2. Calorific value and moisture content of the samples

The most important parameter to characterize a substance as combustible is the calorific value. This is defined as the amount of heat given off when it is burned, with an excess of oxygen, at a given pressure and temperature. It is assumed that the end items of the combustion are O_2, CO_2, SO_2 and N_2 in gaseous phase, and H_2O in liquid phase. The water formed in the combustion comes from the moisture contained in the samples and in the air. There is also water provided by the reaction of the hydrogen contained in the dry sample.

Two calorific values are defined:

- Gross calorific value (GCV), assuming that the water generated in the combustion is in liquid state.
- Net calorific value (NCV), if the water generated in the combustion is in steam state.

The method used in order to determine the calorific value gives the GCV as its result. The difference between the GCV and the NCV is the vaporization energy of the water present in the combustion.

It is assumed that the combustion reaction of dry biomass is the following:

$$C_\alpha H_\beta O_\gamma N_\delta S_\varepsilon A + \left(\frac{2\varepsilon+\beta}{2+\alpha}\right) O_2 = \frac{\beta}{2} H_2O + \frac{\alpha}{2} CO_2 + \frac{\delta}{2} N_2 + \varepsilon SO_2 + \text{ashes} \qquad (1)$$

From Eq. (1) it could be deduced that each mol of biomass produces $\beta/2$ mol of water. So, considering that the molecular weights of H and H_2O are 1 and 18 g/mol, respectively, it is evident that each gram of hydrogen generates nine of water.

The atmospheric air contains humidity, and since in a real combustion oxygen is extracted from it, and the combustible contains moisture, all this water must be considered in the determination of the NCV. Thus, the relation between the GCV and the NCV is the GCV minus the heat necessary to vaporize the water formed in the reaction. Considering that the vaporization heat of water is 2442 kJ/kg [16], the relation between both variables can be expressed as

$$NCV = GCV - 2442 \times 0.01(H_b + H_a) - 2442 \times 0.01 \times 9H_d \qquad (2)$$

where H_d is the % of hydrogen in the dry sample, H_b the % from moisture of the waste and H_a is the % of air humidity in the combustion (the tests were made in an atmosphere of pure O_2, which is why the term H_a is null).

The NCV is most relevant at the time of characterizing a fuel, since it is the one that is usually used in a combustion. The determination of the NCV is not only fundamental at the time of evaluating a substance from a power point of view, but also gives an idea of its inflammability or its potential to generate and to propagate fires. Another important variable in the power study of these wastes is the moisture content. This parameter not only varies with the season of the year in which the sample is collected, but also varies with the time between when the tree is cut down and when it is burned. In order to observe both effects separately, samples throughout the year were taken and they were burned with different moisture content.

3. Ashes

Additionally, the amount of ashes resulting from the combustion of the different species of *Eucalyptus*, has been determined. This is a crucial parameter due to the importance that it has at the time of designing the boilers for this type of fuel [17], and its later management as waste.

The amount of nutrients extracted by these species from the soils of the plantations, which are fundamental data in order to establish fertilization programs. In systems where all the parts of the tree are completely removed from the forest, it is necessary to provide artificial fertilization or to return the ashes to the forest in order to prevent soil impoverishment. This is, therefore, an extra cost that has to be taken into account [18,19]. In this work a chemical analysis of ashes has not been made, since the mass of ash resulting from the combustion in the calorimeter was not enough to give a sufficiently precise analysis.

4. Material and methods

The first stage of the work in the field was to determine where to collect the samples and of which size they should be to get realistic conclusions. Three zones of each species were chosen to make the study. The plantations were located in the Eastern, Central and Western part of the region, in such a way that the biomass samples were sufficiently representative, Fig. 1. The samples of *E. globulus* were collected at altitudes below 250 m, whereas the samples of *E. nitens* were found between 250 and 500 m.

Once inside each chosen zone, the samples were collected avoiding low or high densities of trees, irregular surfaces, edge effects or any unusual characteristic that causes the tree to differ from what is considered to be the norm. The plantations were also characterized by the type of soil, solar radiation, topography, structure, fertilization programs, etc. All these variables consequently influence the volume and the quality of the wood and wastes [20].

It is necessary to emphasize that the chosen plantations have a surface between 30 and 150 ha, in which young and adult trees coexist. From each selected area, two adult trees were cut and then several samples of each part that comprise the waste were extracted. The forest wastes are obtained from several parts of the tree, leaves, thick branches (3 cm < diameter <7 cm), thin branches (diameter < 3 cm), seeds and bark. An analogous process was carried out with young trees, for which neither thick branches nor seeds exist.

Once the samples were collected and classified, they were transported to the Energy Laboratory of the University of Cantabria, where they were weighed and burned with different moistures. The elementary chemical analysis (*Carlo Erba* 1108) was provided by an external Institute.

From each sample, several portions (approximately 1 g) were extracted (moisture included). One part of them was used to analyze the moisture percentage, and the other was burned in a calorimeter to evaluate its potential energy with maximum moisture. The rest of the portions were left in a natural drying process, in order to be subsequently analyzed with inferior moistures. To make the work easier, some common tools in forest tasks were used. The height measuring was made with a hypsometer Vertex, with a sensibility equal to 0.1 m, and the diameter with a caliper (500–650 mm).

The material used in the laboratory for the characterization of the wastes consisted of a moisture analyzer, a precision balance, and a calorimeter. The moisture analyzer is electronic, model Sartorius MA145, and allows the measurement of the relative water content of the different parts that compose the wastes, with a sensitivity of 0.01%. Its operation principle is based on the method of thermogravimetry. So, first the sample is weighed, then it is dried with infrared radiation, and finally it is weighed again, this being a destructive trial.

The samples analyzed in the calorimeter were previously weighed with a balance whose sensibility is 0.1 mg, model Sartorius BP 121S.

The combustion experiments have been made in a calorimeter, model IKA C 5000. This calorimeter is able to analyze combustible in liquid or solid form, making the combustion in an atmosphere of O_2 (99.99995% pure, provided by Air Liquide, Spain), which assures the complete combustion of the sample. The calorimeter can be operate in two operation ways, one adiabatic (without thermal losses), according to the standard DIN, and another isoperibolic (constant reference temperature), according to the standard ASTM. Before the beginning of each session of tests (every 2 months), the calorimeter must be calibrated, for which six combustions with benzoic acid have to be made (GCV = 26,455 ± 20 J/g). The calibration process can be deemed satisfactory when the dispersion of the error is inferior to 0.2%.

5. Results and discussion

The characteristics of the studied plantations are presented in Table 2. The physical and climatic parameters are of great importance in the forest production of the region.

Using the climatic data for each plantation [21], the bioclimatic diagrams were made. The accomplishment of these diagrams was based on the hypothesis that residual evapotranspiration in mm, (*e*), is equal to 20% of the evapotranspiration in mm (ETP). Due to the similarity between some of them, only the two most representative are shown in Figs. 2 and 3, where T is the mean temperature in °C, IBR the real bioclimatic intensity in

Fig. 1. Location of the plantations in Cantabria.

Table 2
Characterization of the plantations

	Eucalyptus globulus						*Eucalyptus nitens*					
	Liendo		Carcena		Corona		Guriezo		Campos de Estrada		Cabanzon	
Soil	Amphibolite		Clayey		Sandy		Sandy		Clay-muddy		Neis	
Slope (%)	10		4		2		19.5		20		18.3	
Height (m)	110		130		98		325		480		475	
Orientation	East		Southeast		Northeast		Southeast		Southwest		North	
Density (stems/ha)	1500		1800		1800		1600		1400		1500	
Age (years)	13	1.4	12	2	11	1	15	1.1	14	1.7	7	2.1
D_s (cm)	14.4	6.5	41.0	9.5	40.1	7.2	16.1	6.7	21.3	9.3	18.3	10.2
H_m (m)	19.1	–	22.9	–	21.0	–	21.2	–	23.7	–	13.8	–
H_0 (m)	22.0	1.8	26.1	3.7	23.8	3.2	24.8	3.0	26.8	4.6	16.8	5.1
Mean annual temperature (°C)	13.8		13.8		13.9		11.1		11.2		10.7	
Annual rain fall (mm)	1112		1340		1172		1780		1679		1486	
Mediterraneanity index	1.80						2.80					

bcu, HA the hydric availability in mm, and 7.5 °C the minimum temperature for vegetal activity.

The analysis of the diagrams showed that the stands do not have vegetation shutdown during the winter. In the plantations of the coastal zone (*E. globulus*, Fig. 2), it is in the months of summer where the real bioclimatic intensity is inferior to the potential one, due to the drought. This effect does not occur in the interior zones (*E. nitens*, Fig. 3), in which growth reduction caused by water shortage does not exist. The diagrams show the great potential of forest production in the region. On the other hand, the influence of physical and geographic parameters in the power values is negligible. For this reason, only the average values of the six plantations are presented.

Before showing the results of calorific values, it is necessary to indicate that these are influenced by a great number of variables which could vary the final value. Here, the importance of seasonality and the variation of the moisture content in the sample have been studied. Other specific variables relative to the place and even to the individual could exist. This means a multitude of scenarios that make a complete study unfeasible. Among the most representative are the geographical orientation of the plantation and the type of soil. Each individual tree's own characteristics are related to its genetic parameters. Due to this multitude of conditions, difficult to quantify, the results must be looked at from the perspective of the peculiarities specific to this study.

In the future, those genetically superior individuals (trees plus), in terms of biomass production in a specific period of time, will be cloned and will form the future plantations. In order to characterize one of these clones, the amount of biomass generated by hectare [22], the percentage of the different parts that constitutes the tree and the calorific values of these parts should be determined. In this way, the power characterization of this type of plantations, in which the amount of energy per hectare is measured in (MJ/ha), will eliminate the influence of the genetic variability.

In Table 3, the annual variation of the average values of the GCV, with the standard deviation and the error for all the samples of the species studied, at maximum moisture (after collection) is presented.

The variation of the GCV throughout the year is fundamentally associated to the fluctuations of moisture and concentration

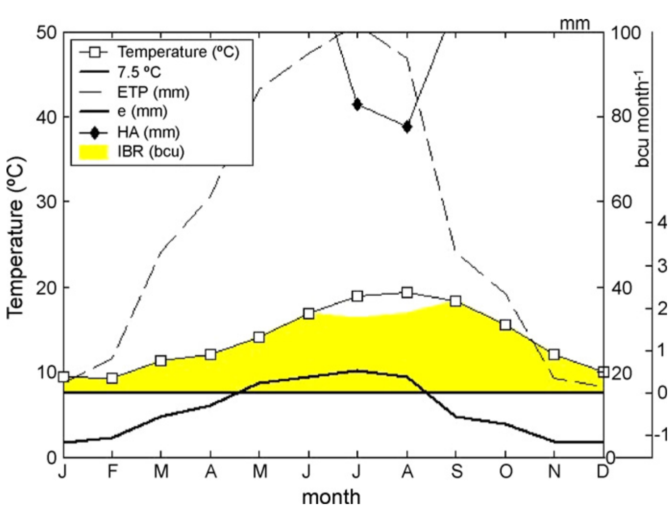

Fig. 2. Bioclimatic diagrams for the plantations of *Eucalyptus globulus*.

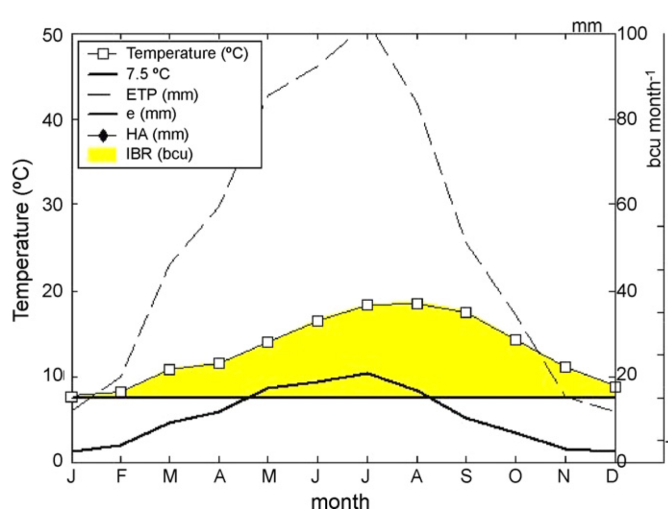

Fig. 3. Bioclimatic diagrams for the plantations of *Eucalyptus nitens*.

Table 3
Annual variation of the GCV (kJ/kg) at maximum moisture

	Winter	Spring	Summer	Autumn
E. globulus				
Adult				
Leaves	12,568 ± 123.17 (0.98%)	12,848 ± 120.77 (0.94%)	13,789 ± 125.48 (0.91%)	14,127 ± ±122.9 (0.87%)
Thick branches	7968 ± 81.27 (1.02%)	7829 ± 87.68 (1.12%)	8142 ± 91.19 (1.12%)	8251 ± 56.11 (0.68%)
Thin branches	7912 ± 88.61 (1.12%)	7621 ± 100.60 (1.32%)	7526 ± 57.20 (0.76%)	7412 ± 92.65 (1.25%)
Bark	6231 ± 61.06 (0.98%)	5908 ± 50.22 (0.85%)	6587 ± 101.44 (1.54%)	7002 ± 78.42 (1.12%)
Seeds	11,489 ± 98.81 (0.86%)	11,564 ± 100.61 (0.87%)	12,582 ± 164.82 (1.31%)	12,497 ± 169.96 (1.36%)
Young				
Leaves	11,244 ± 115.81 (1.03%)	11,780 ± 126.05 (1.07%)	11,874 ± 125.86 (1.06%)	12,573 ± 133.27 (1.06%)
Thin branches	9213 ± 105.95 (1.15%)	9117 ± 106.67 (1.17%)	9236 ± 90.51 (0.98%)	9451 ± 104.91 (1.11%)
Bark	9487 ± 74.95 (0.79%)	9164 ± 120.96 (1.32%)	10,234 ± 91.08 (0.89%)	10,561 ± 96.11 (0.91%)
E. nitens				
Adult				
Leaves	16,927 ± 159.11 (0.94%)	17,033 ± 166.92 (0.98%)	17,865 ± 133.99 (0.75%)	17,949 ± 148.98 (0.83%)
Thick branches	9127 ± 110.44 (1.21%)	9013 ± 77.51 (0.86%)	9102 ± 101.94 (1.12%)	9270 ± 81.58 (0.88%)
Thin branches	12,780 ± 143.14 (1.12%)	12,105 ± 99.26 (0.82%)	13,121 ± 161.39 (1.23%)	12,856 ± 18.00 (0.14%)
Bark	7009 ± 55.37 (0.79%)	7010 ± 86.22 (1.23%)	7564 ± 74.13 (0.98%)	7324 ± 17.58 (0.24%)
Seeds	11,259 ± 118.22 (1.05%)	11,150 ± 171.71 (1.54%)	11,875 ± 160.31 (1.35%)	12,141 ± 108.05 (0.89%)
Young				
Leaves	10,572 ± 130.04 (1.23%)	10,482 ± 148.84 (1.42%)	11,008 ± 138.70 (1.26%)	11,239 ± 125.88 (1.12%)
Thin branches	9245 ± 72.11 (0.78%)	8919 ± 99 (1.11%)	9163 ± 151.19 (1.65%)	9214 ± 62.66 (0.68%)
Bark	9657 ± 96.57 (1.00%)	9388 ± 102.33 (1.09%)	9524 ± 143.81 (1.51%)	9711 ± 127.21 (1.31%)

of volatile substances and essential oils. The periods in which greater concentrations appear coincide with the maximum vegetable activity. The highest GCV is reached in autumn, which is due to the minor moisture of the samples at the moment of their harvesting. Thus, the leaves of *E. nitens* in adult stage give an average value of 17,949 kJ/kg, whereas in the young stage it is the leaves of *E. globulus* that give the greatest GCV, with a value of 12,573 kJ/kg. The bark is the part of the waste that gives the smallest GCV. In adult stage the *E. nitens* is the one that reaches the greatest value, with a maximum value of 7324 kJ/kg, while the *E. globulus* obtains 7002 kJ/kg.

Perhaps, the most remarkable fact in this research is that the *E. nitens* gives more power than the *E. globulus* in the adult stage, which happens in all the parts of wastes except in seeds. This is justified because the *E. nitens*, in the adult stage, has a greater concentration of volatile components and essential oils than the *E. globulus* [23]. These substances have a GCV superior to 40,000 kJ/kg [24], which is very important for the GCV of the wastes. Nevertheless, the same thing does not occur in the young stage, where it is the *E. globulus* that presents better power values, although their leaves have suffered the sequels of the fungus *Mycospharella* spp.

The part, in weight, of each component of the tree [25], is indicated in Table 4. The greater part of the adult tree corresponds to useful wood, the total waste left in the plantations being 20% of the weight of the tree. In Fig. 4 the annual averages of GCV and NCV, at maximum and minimum moisture, are shown. Moreover, the GCV of each part and the percentage, in weight, over the total waste have been taken into account (Table 4).

Observing Fig. 4, the calorific value of the wastes for both species in their two stages of growth can be compared.

Table 4
Percentage, in weight, of each part of the tree

	E. globulus		*E. nitens*	
	Young (%)	Adult (%)	Young (%)	Adult (%)
Leaves	38.96	2	41.66	2.2
Wood and thick branches	–	81.06	–	79.69
Thin branches	53.00	8.4	49.20	10.3
Bark	8.04	7.4	9.14	7.6
Seeds	–	1.14	–	0.21

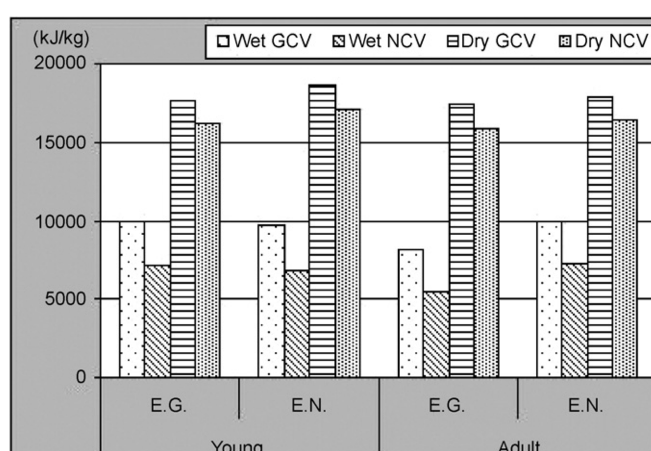

Fig. 4. Comparison of the average calorific value of the two species at maximum moisture and dryness.

Table 5
Annual average of the GCV

%W	Leaves	%W	Thin branches	%W	Bark
E. globulus					
Adult					
40–43	12,848 ± 123.33 (0.93%)	42–45	7021 ± 84.75 (1.11%)	61–64	5908 ± 72.2 (1.12%)
27–30	17,587 ± 195.22 (1.11%)	29–31	12,333 ± 115.93 (0.94%)	45–48	6440 ± 87.58 (1.36%)
15–18	19,432 ± 190.43 (0.98%)	10–13	16,677 ± 165.10 (0.99%)	15–18	14,927 ± 135.84 (0.91%)
0–3	19,593 ± 209.64 (1.07%)	0–3	18,567 ± 232.09 (1.25%)	0–3	15,712 ± 196.4 (1.25%)
Young					
51–54	11,780 ± 125.21 (1.06%)	48–51	9017 ± 108.73 (1.10%)	46–49	9164 ± 77.73 (0.84%)
26–29	12,741 ± 131.23 (1.03%)	36–39	11,653 ± 75.74 (0.65%)	20–23	9483 ± 124.23 (1.31%)
11–14	14,980 ± 146.8 (0.98%)	11–14	14,554 ± 139.72 (0.96%)	10–13	13,879 ± 174.88 (1.26%)
0–3	16,453 ± 143.14 (0.87%)	0–3	18,332 ± 203.49 (1.11%)	0–3	16,229 ± 321.33 (1.98%)
E. nitens					
Adults					
26–29	17,033 ± 152.64 (0.88%)	32–35	12,105 ± 105.22 (0.83%)	52–55	7010 ± 60.56 (0.81%)
18–21	18,428 ± 187.97 (1.02%)	20–23	14,008 ± 145.68 (1.04%)	28–31	11,235 ± 108.98 (0.97%)
9–12	21,005 ± 277.27 (1.32%)	8–11	16,571 ± 160.74 (0.97%)	12–15	14,338 ± 207.9 (1.45%)
0–3	22,551 ± 270.61 (1.20%)	0–3	18,509 ± 164.73 (0.89%)	0–3	16,402 ± 200.1 (1.22%)
Young					
54–57	10,482 ± 136.12 (1.26%)	51–54	8919 ± 96.37 (1.06%)	39–42	9388 ± 117.47 (1.23%)
21–24	17,486 ± 160.87 (0.92%)	29–32	10,127 ± 80 (0.79%)	28–31	12,987 ± 129.87 (1%)
13–16	18,287 ± 181.04 (0.99%)	9–12	12,384 ± 125.08 (1.01%)	11–14	15,536 ± 181.77 (1.17%)
0–3	19,353 ± 193.53 (1.00%)	0–3	18,499 ± 196.09 (1.06%)	0–3	17,647 ± 174.71 (0.99%)

%W	Thick branches	%W	Seeds
E. globulus			
42–45	7829 ± 79.27 (0.99%)	58–61	9314 ± 132.36 (1.10%)
35–38	11,004 ± 97.94 (0.89%)	23–26	14,860 ± 169.4 (1.14%)
10–13	16,499 ± 188.09 (1.14%)	7–10	18,800 ± 231.24 (1.23%)
0–3	18,645 ± 225.60 (1.21%)	0–3	15,279 ± 126.82 (0.83%)
E. nitens			
51–54	9013 ± 92.88 (1.02%)	40–43	11,150 ± 140.14 (1.21%)
22–25	12,740 ± 124.85 (0.98%)	21–24	14,972 ± 143.73 (0.96%)
8–11	16,760 ± 221.23 (1.32%)	5–8	18,835 ± 233.55 (1.24%)
0–3	18,643 ± 162.19 (0.87%)	0–3	19,939 ± 223.32 (1.12%)

From the power point of view of the energy obtained, the wastes of *E. nitens* are superior to those of *E. globulus*. These results are very important since they integrate percentages of each part with respect to the whole tree, with their respective inferior calorific values, with the NCV being obtained from the waste.

In Table 5 the variation of the annual averages of the GCV of the different parts from the wastes of *E. globulus* and *E. nitens*, for different moisture content, are presented. The strong dependency between the GCV and the moisture makes a waste predrying process prior to burning advisable. For example, the leaves of *E. nitens* present, at the moment of the harvesting, an annual GCV average 17,033 kJ/kg, whereas at minimum moisture this value is 22,551 kJ/kg. A similar effect can be appreciated with the rest of tree parts.

Other forest species that can be used as energy crops, show results of calorific values for *poplar clone bark* of 19,667 and 17,473 kJ/kg [26,27]. These values are similar to those obtained for the bark of *E. globulus* and *E. nitens* in this work.

In Table 6, the annual average of the elementary chemical analysis of the different parts that compose the wastes, for both species in the two stages of growth studied.

Because the fertilization programs used in the plantations selected were similar, small variations are observed. Perhaps, in plantations without fertilization and in different soils, the percentage could be more variable, especially in the percentage of nitrogen and sulphur.

In Table 7, the average of the resulting ashes after each combustion in the calorimeter appears. It is observed, in both species, that the greater amount of ashes corresponds to leaves and bark, which indicates that it is in these parts where more nutrients are accumulated. The maximum percentage of ash is provided by the bark, with 7.1% and 6.3% in the adult stages of *E. nitens* and *E. globulus*, respectively, whereas in the young stage it is 4.5% for *E. nitens* and 7.2% for *E. globulus*.

This fact is related to the existence in leaves and bark of a greater concentration of nonvolatile nutrients (K: potassium; P: phosphorus; Mg: magnesium; Ca: calcium; Na: sodium, etc.) than in the wood. The amounts of nitrogen accumulated in the biomass are substantially inferior to the reserves of this element potentially available in the ground [18,19]. The contributions of rain and some alterations are not sufficient to replace the calcium and other nutrients (Mg, P, etc.) extracted with the biomass of the plantations [28]. In Cantabria, sulphur is found in greater

Table 6
Annual average of the elementary chemical composition of the samples of *E. globulus* and *E. nitens*

	H	C	N	S	O (by diff.)
E. globulus					
Adult					
Leaves	7.27	54.01	1.41	0.22	37.09
Thick branches	6.98	46.01	0.75	0.13	46.13
Thin branches	7.13	50.09	0.54	0.09	42.15
Bark	6.60	49.92	0.65	0.20	42.63
Seeds	7.11	44.91	1.21	0.11	46.66
Young					
Leaves	7.02	55.47	1.57	0.18	35.76
Thin branches	6.45	51.17	0.98	010	31.4
Bark	7.24	49.06	0.86	0.08	42.76
E. nitens					
Adult					
Leaves	7.12	56.89	1.31	0.16	34.52
Thick branches	6.78	48.16	0.78	0.21	44.07
Thin branches	6.85	53.24	0.68	0.25	38.98
Bark	7.22	57.31	0.71	0.14	34.62
Seeds	6.92	45.03	1.06	0.09	46.9
Young					
Leaves	7.26	56.02	1.56	0.19	34.97
Thin branches	7.28	48.25	0.73	0.14	43.6
Bark	7.09	54.72	0.87	0.08	37.24

Table 7
Percentage, in weight, of the ashes with respect to the dry weight of wastes

	E. globulus	*E. nitens*
Young		
Leaves	7.4	2.5
Thin branches	2.7	1.8
Bark	7.2	4.5
Average	4.89	2.34
Adult		
Leaves	5.8	1.5
Thick branches	3.4	2.2
Thin branches	2.8	1.1
Bark	6.3	7.1
Seeds	2.4	2.3
Average	4.59	3.68

concentrations than those accumulated in the biomass. This is due to the generally acid nature of its soils.

In order to avoid the loss of fertility in soils, it would be necessary to give back to the plantation the ashes from the combustion or to create programs of artificial fertilization. From the logistic and economic point of view, the contribution of artificial fertilization is more advantageous than the return of ashes [25]. In this aspect, it is necessary to indicate that, depending on the costs of CO_2 emission, the economic viability will depend to a great extent on the energy extracted from these wastes.

Considering the species studied, a lower average percentage of ashes is observed in the *E. nitens*, which has a positive influence on its costs with respect to the *E. globulus*. So, this is summarized in two aspects: a smaller amount of nutrients to be provided per hectare of plantation and lower cleaning and maintenance costs of the boilers in which the combustion is carried out.

Assuming an average wood production per ha and year like the one indicated in Table 8 [25], a yield in the electrical generation of 20% [29], and a electricity price of 6.7 c€/kWh [30], it is possible to estimate the production of the region of Cantabria, and what the collection of this waste would mean in economic terms. For this, the total surface dedicated to the growth of *E. nitens*, 5906 ha, and *E. globulus*, 23,610 ha, have been considered. Taking into account the analysis performed, it is observed that if the wastes of both species of *Eucalyptus* currently cultivated in the region were collected, they would produce an important annual income. The sale of electricity obtained from these wastes could generate 1.06 M€ for the *E. nitens*, and 2.75 M€ for the *E. globulus*.

From the environmental point of view, the benefit provided by the average production previously described, in tonnes of CO_2 fixed per ha and year, has been calculated. Moreover, although the combustion of the wastes releases into the atmosphere the CO_2 fixed previously to trees, the carbon balance is positive since a part of the carbon is permanently trapped in the roots and soil (organic horizon) [18]. On the other hand, the part corresponding to the wood will be transformed into elements of lasting nature (furniture, paper, etc.). Thus, the carbon will be held in them quasi-permanently.

The high growth of the species studied implies a great productivity per ha for this type of plantation. The results of Table 9

Table 8
Annual economic evaluation per ha

	Wastes (kg/(ha year))	NCV (kJ/kg)	Electric efficiency (%)	Electricity (kWh/(ha year))	c€/kWh	€/(ha year)	M€/year
E. globulus	5702	5478	20	1735.3	6.7	116.3	2.75
E. nitens	6624	7289		2682.3		179.7	1.06

Table 9
Annual environmental analysis per ha

	Wood (m^3)	Density (kJ/kg)	Wood (kg)	Waste (kg)	%C in wood	%C in waste	C in wood (kg)	C in wasted (kg)	C total (kg)	Fixed CO_2 (kg/(ha year))
E. globulus	32	785	25,120	5869	52.80	49.42	13,263	2900	16,164	64,656
E. nitens	37	696	25,752	6563	53.12	50.99	13,679	3346	17,026	68,105

reveal that these types of plantations are real carbon drains. Thus, an average plantation of *E. globulus* would fix annually 64.5 t of CO_2 per ha, while the *E. nitens* would fix 68.1 t.

6. Conclusions

From the power point of view, the wastes of the *E. nitens* are slightly better than those of the *E. globulus*, and this in spite of the greater commercial interest of the *E. globulus* for the paper industry. This power superiority appears in the complete moisture range and is associated to a greater concentration of volatile substances and essentials oils.

In both species the part which the best calorific value is the leaves. For the optimization of the cultivation of these species, the leaves will be the part to maximize.

The energy analysis has shown that the calorific value could be duplicated by drying the sample. The strong dependency between the GCV and the moisture makes a waste predrying process prior to burning advisable.

In Cantabria the use of the forest wastes of *E. globulus* and *E. nitens* for electrical generation, would mean an approximate energy of 57 GWh. This could produce an annual income of 3.8 M€, since this type of energy is considered to be within a special regime.

The calorific values vary throughout the year, mainly due to the moisture variation and to the concentration of volatile and aromatic substances. The study has shown that there are no important differences between the calorific values obtained, even when the geographic and soils characteristics vary for the different plantations. So the data of the work is exportable to other places with similar bioclimatic characteristics.

The collection of the wastes supposes a gradual impoverishment of the soil, which could be prevented by means of fertilization programs. Thus, the ashes resulting from the combustion can be used for this objective, as well as artificial fertilizations. This first option has a greater cost, as much economic as logistic.

Finally, the environmental balance shows that the use of species as energy crops, in the non-forest surface of Cantabria, would fix 40% of the CO_2 assigned by Environment Ministry to the region. This is an interesting economic alternative for the Carbon Emissions Market, which is a mechanism proposed by the Kyoto Protocol.

Acknowledgments

The authors wish to thank the Council on Research and Technological Development of the University of Cantabria for their financial support; the company Bosques 2000 S.L. for its great help; and the Forest Department of the Government of Cantabria for its support in the collection of samples and data.

References

[1] http://www.idae.es.
[2] K. Pingoud, A. Lehtilä, I. Savolainen, Environ. Sci. Police 2 (1999) 153–163.
[3] Hubbard., et al., Experimental Thermochemistry, Interscience, New York, 1956.
[4] E. Ralfh, H. Sims, K. Senelwa, et al., Biomass Bioenergy 16 (1999) 199–205.
[5] F. Sanz, G. Piñeiro, CIS-Madera 10 (2003) 6–37.
[6] M. Lemenih, T. Bekele, Biomass Bioenergy 27 (2004) 223–232.
[7] L. Núñez, et al., Bioresour. Technol. 82 (2002) 5–13.
[8] S. Perez, C.J. Renedo, D. Silió, A. Ortiz, M. Mañana, ICREPQ'05, Zaragoza, Spain, 2005.
[9] 3° *Inventario Forestal*. Gobierno de Cantabria. Dirección General de Montes y Conservación de la Naturaleza, 2004.
[10] *Plan Forestal de Cantabria*, Gobierno de Cantabria. Dirección General de Montes y Conservación de la Naturaleza, 2004.
[11] http://www.uhu.es/cideu.
[12] M. Balboa, J. Alvarez, Cis-Madera (2003) 27–37.
[13] S. Santolamazza-Carbone, A. Rodríguez-Illamola, A. Cordero, Biol. Contr. 29 (2004) 24–33.
[14] A.R. Clarke, S. Paterson, P. Pennington, For. Ecol. Manage. 110 (1998) 89–99.
[15] Abbott, P. Van Heurck, T. Burbidge, M. Williams, For. Ecol. Manage. 58 (1993) 85–110.
[16] M. Moran, H. Shapiro, *Termodinámica Técnica*. Ed Reverté, 2004.
[17] L. Baxter, et al., Dev. Thermochem. Biomass Convers. 2 (1997) 1278–1292.
[18] J. Brañas, et al., Investigaciones Agrarias 9 (2000) 318–335.
[19] E. Español, et al., Investigaciones Agrarias 9 (2000) 210–217.
[20] R.K. Mistra, C.R.A. Turnbull, R.N. Cromer, A.K. Gibbons, A.V. LaSala, For. Ecol. Manage. 106 (1998) 283–293.
[21] J.L. Montero, J.L. Gonzalez, Diagramas Bioclimáticos, ICONA, Ministerio de Agricultura, Pesca y Alimentación, 2002.
[22] M. Battaglia, P.J. Sands, S.G. Candy, For. Ecol. Manage. 120 (1999) 193–201.
[23] K. Senelwa, R. Sims, Biomass Bioenergy 17 (1999) 127–140.
[24] E. Martín, F. Lara, Inflamabilidad y Energía de las Especies del Sotobosque, Ed Instituto Nacional de Investigaciones Agrarias, Ministerio de Agricultura, Pesca y Alimentación, 1989.
[25] Bosques, S.L. Departamento de Investigación y Desarrollo (Internal data), 2000.
[26] T.F. Strong, Energy Values of Nine Populus Clones North Central Forest Experiment Station, Rhinelander, Wisconsin, 1992.
[27] B. Klasnja, S. Kopitovic, S. Orlovic, Wood and bark of some poplar and willow clones as fuelwood, Biomass Bioenergy 23 (2002) 427–432.
[28] E. Dambrine, B. Pollier, M. Bonneau, N. Ignatova, Use of artificial trees to assess dry deposition in Spruce stands, Atmos. Environ. 32 (10) (1998) 1817–1824.
[29] S. Perez, C.J. Renedo, D. Silió, A. Ortiz, M. Mañana, IV Jornadas Nacionales de Ingeniería Termodinámica, Logroño, 2005.
[30] http://www.ree.es.